OAK RIDGE NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION
NUCLEAR DIVISION
for the
U.S. ATOMIC ENERGY COMMISSION

ORNL-TM-2196

HFIR FUEL ELEMENT PRODUCTION AND OPERATION

G. M. Adamson, Jr., and R. W. Knight

ORNL-TM-2196

Contract No. W-7405-eng-26

METALS AND CERAMICS DIVISION

HFIR FUEL ELEMENT PRODUCTION AND OPERATION

G. M. Adamson, Jr., and R. W. Knight

Paper presented at the AEC Industry Meeting, Water Reactor Fuel Element Technology, January 29–30, 1968, Washington, D. C.

JUNE 1968

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

ORNL-TM-2196

Contract No. W-7405-eng-26

METALS AND CERAMICS DIVISION

HFIR FUEL ELEMENT PRODUCTION AND OPERATION

G. M. Adamson, Jr., and R. W. Knight

Paper presented at the AEC Industry Meeting,
Water Reactor Fuel Element Technology,
January 29–30, 1968, Washington, D. C.

JUNE 1968

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

CONTENTS

Page

Abstract 1

Introduction 1

Reactor Operation 2

Examination of Irradiated Element 3

Element Fabrication Results 8

Fuel Plate Rejects 9

Cladding Thickness 11

Edge Cladding 12

Water-Channel Spacing 14

Element Waiver Summary 15

Conclusions 16

HFIR FUEL ELEMENT PRODUCTION AND OPERATION

G. M. Adamson, Jr., and R. W. Knight

ABSTRACT

The High Flux Isotope Reactor has been in operation for over two years and at full power for one and one-half years with no fuel element problems — the satisfactory performance being indicated by both the reactor operation and the hot-cell examination of a burned element. Areas in the fuel plates with burnups estimated as high as 18.6×10^{20} fissions/cm^3 showed no significant irradiation damage. Gamma scans of the plates confirmed that the desired flux profiles had been obtained.

Data are presented showing that these complex HFIR fuel elements can be produced commercially with the excellent recovery rate of 88.2% for a total of over 30,000 plates. The major causes of plate rejection were surface defects and nonbonds. Excellent control was achieved of the cladding thickness, fuel core dimensions, and water-channel spacing.

While 45 fuel assemblies have been delivered and all have been accepted for full-power use, only four inner elements have not required minor waivers of some kind. The waivers arose from a variety of causes. There is no requirement in the specifications that we have been unable to meet, and with a few minor exceptions no problems have occurred with sufficient frequency to require a change in the specifications.

INTRODUCTION

An earlier discussion[1] covered how research reactor fuel elements, including those for HFIR, are fabricated. In this paper we will briefly discuss how the HFIR fuel elements are performing and what information and results are available from their commercial fabrication. Obviously the work of many individuals at both ORNL and Metals and Controls has been incorporated into this presentation.

[1] G. M. Adamson, Jr., "Fabrication of Research Reactor Fuel Elements," paper presented at the AEC Industry Meeting, Water Reactor Fuel Element Technology, January 29–30, 1968, Washington, D. C.; also ORNL-TM-2197 (in press).

REACTOR OPERATION

The HFIR reactor system has performed astoundingly well. It has been in almost continuous operation for two years and at full power for over one and one-half years with very few problems. The outputs from the fuel elements are given in Table 1. The consistency of the operating exposures is very gratifying for such a new machine, especially one pushing the technology as far as this one did. In only a single case was the reactor shut down by a possible fuel element problem. This was not a mandatory shutdown, and it now appears to have been due to an incorrect judgment, so the element will be returned to the reactor.

Table 1. Operating History of HFIR Fuel Elements

Element Cycle Number	Power (Mw)	Exposure (Mwd)
1	20	(1300)
	50	2230
2	75	2310
3	90	2349
4	100	2046
5	100	2266
6	100	2326
7	100	2360
8	100	2360
9	100	2362
10	100	2366
11	100	575[a]
12	100	2306
13	100	2026[b]
14	100	2296
15	100	2308
16	100	2309
	Average	2281

[a]This element was removed but will be returned to the reactor, so it was not included in the average.

[b]Power outage occurred at 2026 Mwd. Element would not come back to power due to fission-product buildup during shutdown and lack of excess reactivity.

Table 2 lists some of the performance criteria for this reactor. These data are more impressive when you remember that they are achieved with a garbage-can-size aluminum system — not stainless steel or zirconium.

Table 2. Performance Criteria for HFIR

Characteristic	Value
Reactor power, kw	100,000
Power density, kw/liter	
Average	2,000
Maximum	4,000
Heat flux, Btu hr^{-1} ft^{-2}	
Average	800,000
Maximum	2,100,000
Neutron flux, neutrons cm^{-2} sec^{-1}	
Thermal[a]	5×10^{15}
Fast (>0.8 Mev)[b]	9×10^{14}
Bulk water temperature, °F	
Entrance	120
Exit	170

[a]Unperturbed value for center of flux trap with an all-water island.

[b]In the horizontal midplane at the radial edge of a standard target loading.

Within the limits of the instrumentation, the only change in the elements during operation has been a buildup in oxide. No changes in appearance are visible in the irradiated elements being stored in the pool.

EXAMINATION OF IRRADIATED ELEMENT

An irradiated element is being examined in the hot cells. Preliminary results indicate that the element as removed was sound. Figure 1 shows an outer element in the cell with a fuel plate being cut from the side plate. The excellent appearance of both the inside and outside surfaces is apparent. An end view of the same element in Fig. 2 shows

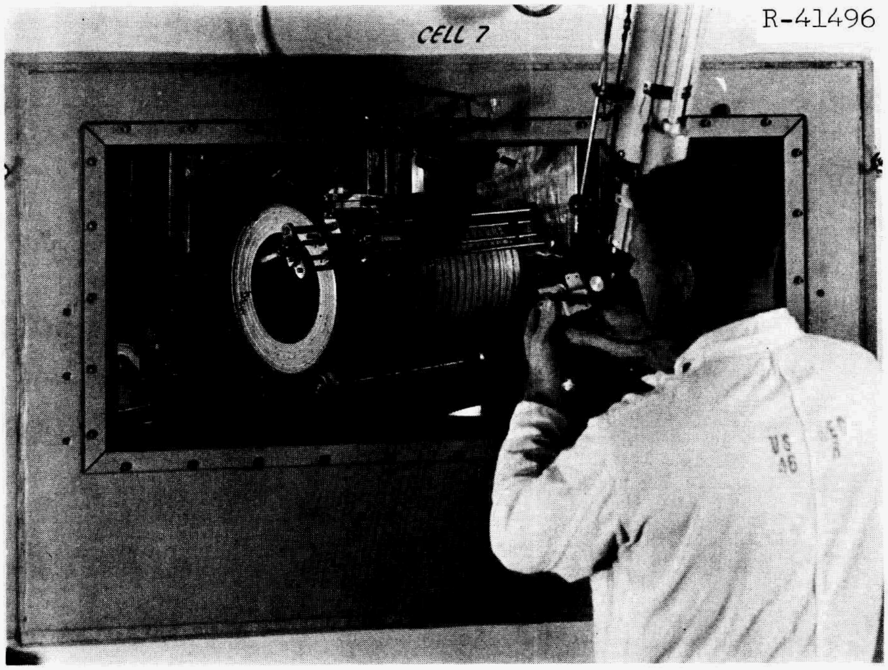

Fig. 1. In-Cell Examination of Irradiated HFIR Fuel Element.

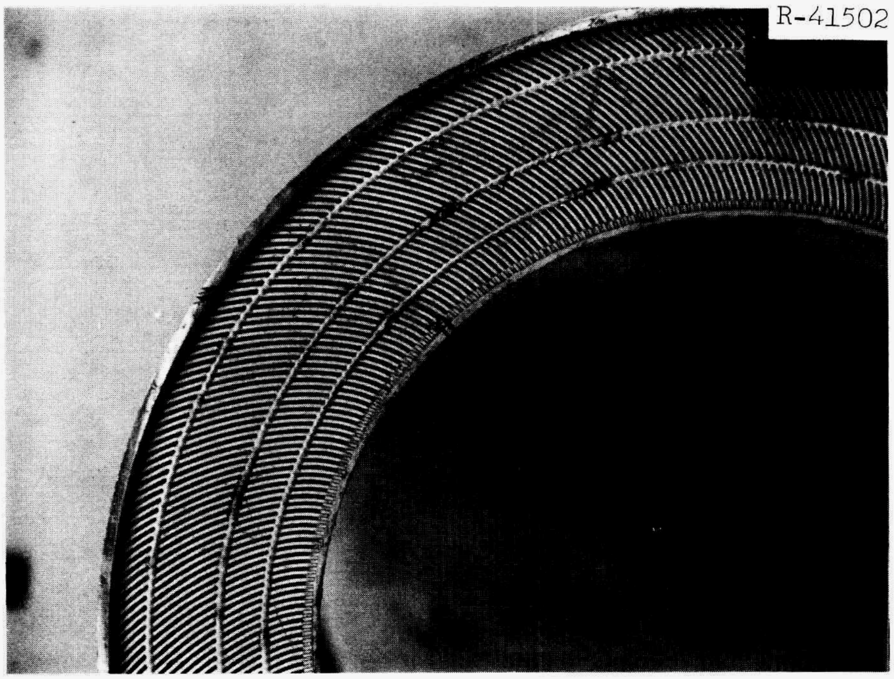

Fig. 2. End View of Irradiated Outer Fuel Element.

the undisturbed condition of the plates. Four fuel plates located approximately 90° apart were cut from the element. As shown in Fig. 3, all show similar surface oxide patterns.

R-41824

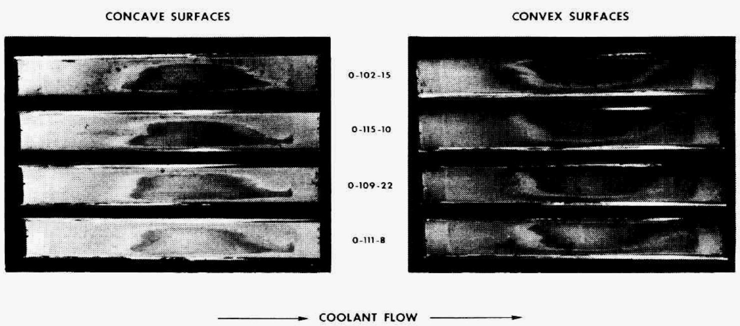

Fig. 3. Surfaces of Fuel Plates from Irradiated Fuel Element.

Some typical values of the burnup are worth noting. On the horizontal midplane, the burnup was 11.4×10^{20} fissions/cm^3 at the inner edge of the fuel region, 6.9×10^{20} fission/cm^3 midway through the fuel, and 18.6×10^{20} fissions/cm^3 at the outer edge. This last value is the peak burnup of the fuel; the nominal fuel core temperature was 285°F at that point. The highest fuel core temperature was 305°F; it occurred slightly below the horizontal midplane at a point where the burnup was 8.5×10^{20} fissions/cm^3. No plate distortion or evidence of blistering was apparent, either before or after descaling. While as detailed an examination cannot be made of the other plates, we can at least say that no major blistering or distortion had occurred.

Data on water-channel spacing and fuel plate thicknesses are still being analyzed but show only minor or no changes.

Presented in Fig. 4 is a gamma scan along the center of a plate. The shape is an indication of the fission density distribution and is quite close to prediction. The smoothness of the curve indicates the excellent homogeneity which had been achieved. Two transverse gamma scans are shown in Fig. 5. The one at the axial center line shows how effective the curved fuel core was in flattening the flux. These were made with the curved plate, and the ends have not been completely corrected for the angle between the plate and the detector.

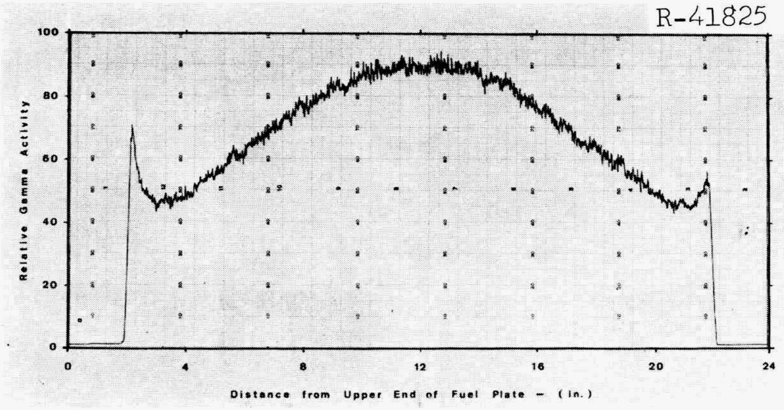

Fig. 4. Longitudinal Gamma Scan of Irradiated Fuel Plate.

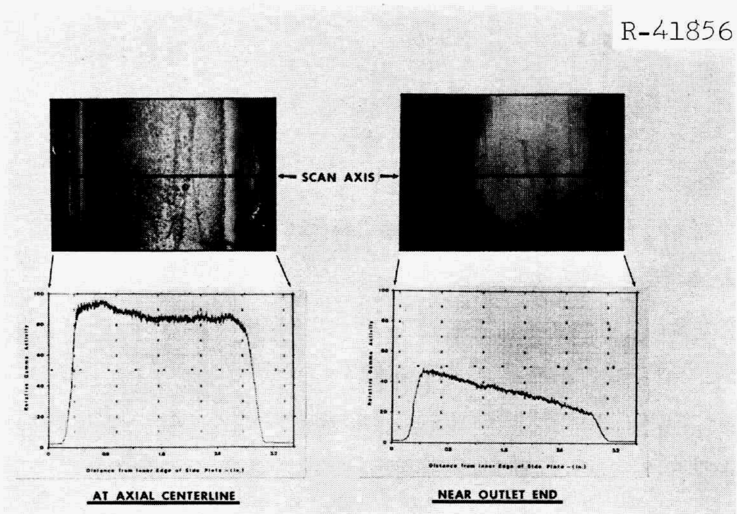

Fig. 5. Surface Characteristics and Transverse Gamma Scans on Plate.

The metallurgical structure found in the central portion of the plate is shown in Fig. 6. This photograph at 100X shows considerable variation in the amount of reaction with the various particles. This variation seems to be characteristic of such dispersions. The amount of reaction is less than had been expected from previous work. Note that there is no evidence of cracking or breaking up of the dispersion. Cracks usually appear first at the ends or sharp protrusions of the particles; none are present at such locations in these specimens. This would be considered as a good dispersion with an almost complete absence of fine fuel particles. Figure 7 shows at higher magnification (250X) the outer edge of the fuel in a section where burnup was the highest. It confirms the previous conclusions. It also shows the small voids in the least reacted portions of the fuel and very large voids in the portions showing the most reaction. At least three different structures are present as indicated by colors.

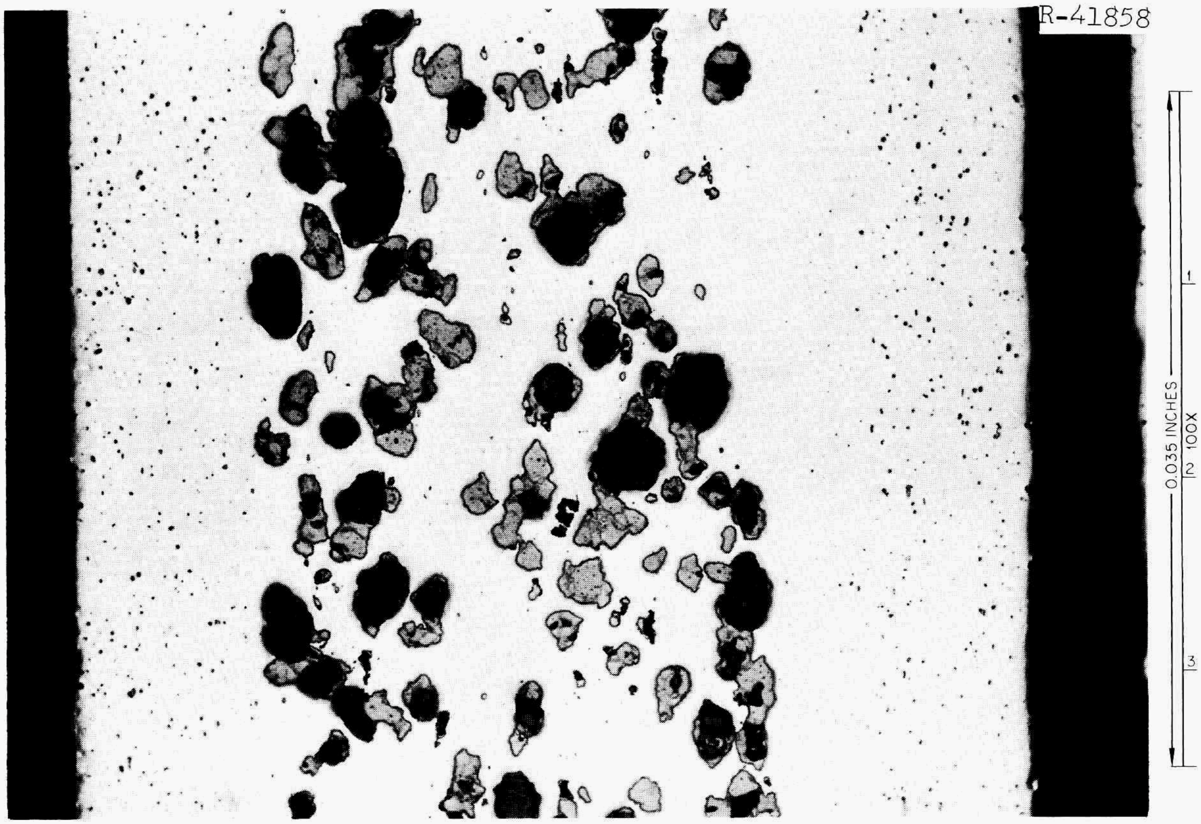

Fig. 6. Metallurgical Structure of Central Portion of Irradiated Plate. Estimated burnup 6.9×10^{20} fissions/cm^3.

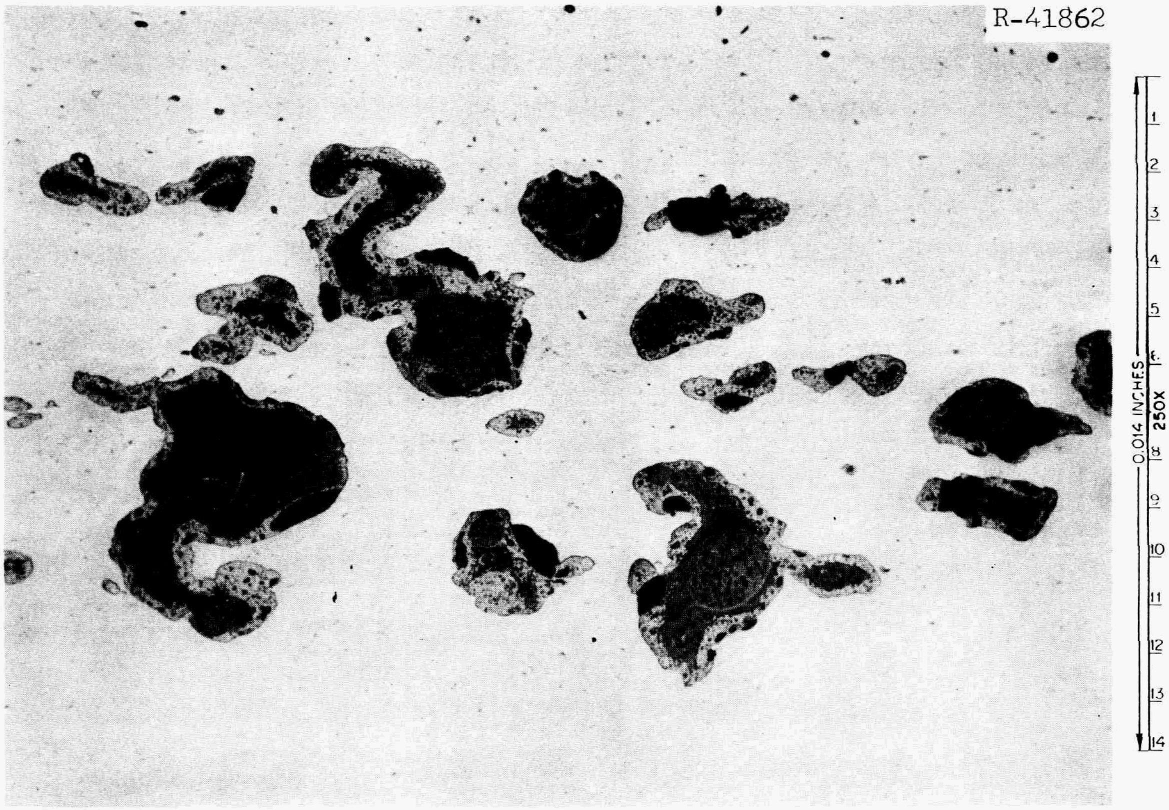

Fig. 7. Metallurgical Structure of Outer Edge of Irradiated Plate. Estimated burnup 18.6×10^{20} fissions/cm^3.

ELEMENT FABRICATION RESULTS

We have shown that the elements have performed satisfactorily, but can an element of such complexity with such tight tolerances be fabricated commercially? We can now answer definitely, "Yes, the present fuel element fabricator (Metals and Controls) is holding to the predicted delivery schedule and has delivered 48 acceptable assemblies." A better feel for the magnitude of this accomplishment may be had by examining the following list, which tabulates some of the tolerances that it has been necessary to meet.

Fuel Plates	Fuel Elements
Core Width Outer fuel plates 2.760 ± 0.024 in. each side	Inner Annulus Critical diameter tolerance — 10.915 ± 0.001 in. (concentricity 0.002 in. TIR) Critical surface flatness — 0.0005 in. TIR
Core Length 20 ± 0.25 in. each end	
Plate Thickness 0.050 ± 0.001 in. 0.0006 in. variation within a plate	Outer Annulus Critical diameter tolerance — 16.754 ± 0.002 in. (concentricity 0.002 in. TIR)
Plate Surface Within the fuel core outline — maximum defect depth 0.002 in.	
Uranium Homogeneity Spot size 5/64 in. Average ±12% over approximately 1-in. length Spot +27% maximum	
Nonbond 1/16-in.-diam maximum	

In the remaining portions of this paper we will present some of the data obtained during the fuel element production. These data will show how well the specifications are being met and what items are causing rejections or trouble.

Fuel Plate Rejects

The causes of fuel plate rejections are summarized in Fig. 8 for the first 30,220 plates produced. From this large number, only 15.7% were rejected and 3.9% of these were accepted by ORNL on waiver, making a loss of 11.8%. Although these figures are good, after 25,000 plates, they were 11.5, 2.3, and 9.2%, respectively. As may be seen by the bars, the major cause of rejections has been surface defects and nonbonds, which include any blisters.

As may be seen by Fig. 9, we have recently experienced a large increase in both of these categories. All others have shown either a

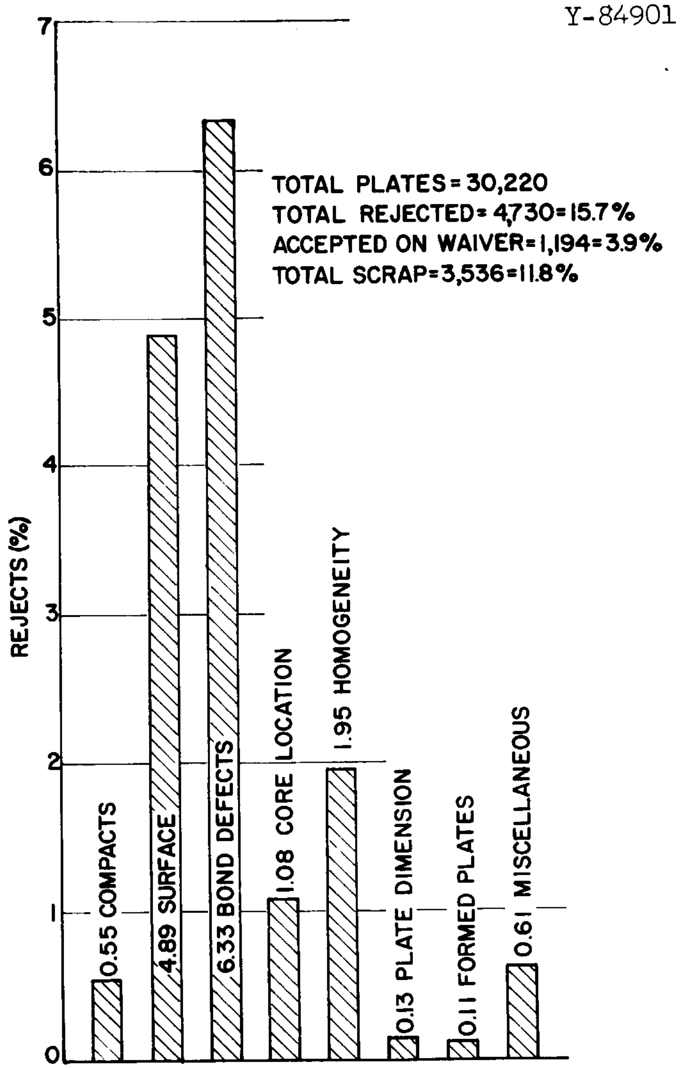

Fig. 8. HFIR Fuel Plate Recovery Data.

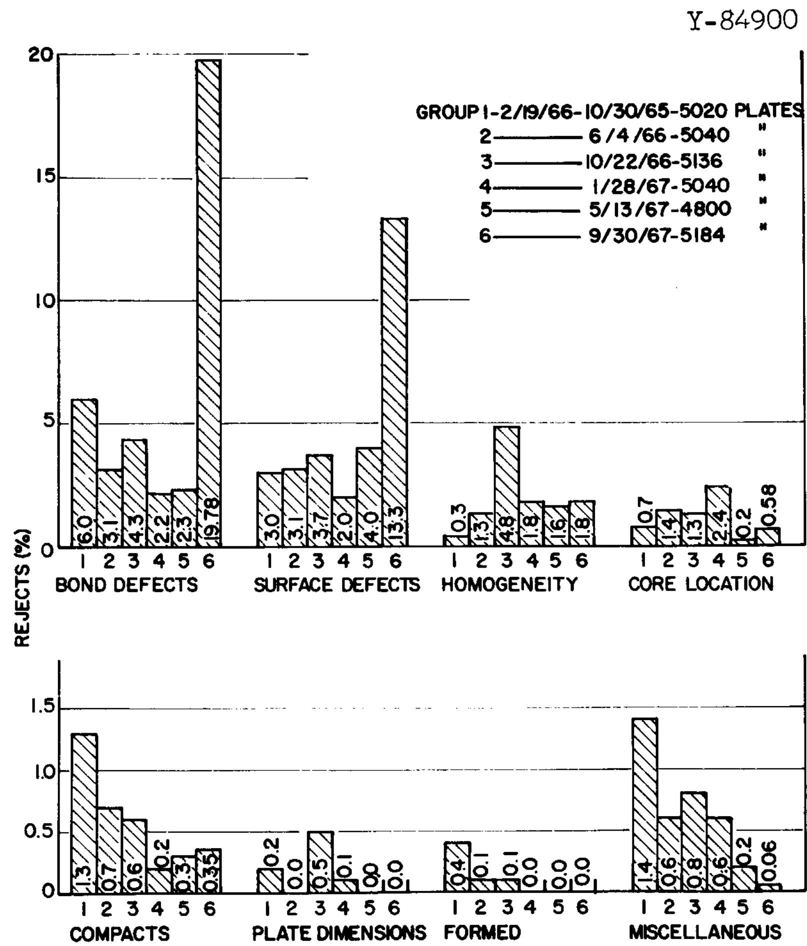

Fig. 9. HFIR Fuel Plate Rejection Data.

decrease or continued at about the same level. With only a 2-mil scratch permitted in dead soft aluminum, we have had to work very hard to keep the surface rejection rates at these levels. The increase in surface rejects was caused by an increase in surface roughness of the plates, which, in excessive cases, might even be mistaken for very small blisters. Both this and the nonbond increase appear to be caused by a slight change in impurities or possibly segregation in starting material, coupled with high rolling and annealing temperatures. Incipient melting in grain boundaries had occurred within the plates. Lowering the rolling temperature 25°F appears to have corrected these difficulties.

Since this is the first time fuel homogeneity has been specified and determined for a surface area as small as 5/64 in., the less than 2% rejection rate is considered quite acceptable.

Cladding Thickness

No plates have been rejected for cladding thickness, despite careful monitoring. Having established a reasonable confidence level, we now destructively examine a minimum of one plate per element, determining both average and minimum cladding thickness from five sections with a total of over 50 measurements. Distribution curves of the measured values for minimum cladding thickness are shown in Fig. 10. The values found were significantly different for the top and bottom cladding but were the same for inner and outer elements. The difference was caused by the filler portion protecting the cladding from penetration by hard fuel particles. The minimum is well above the specified 8 mils.

With average cladding thicknesses, there is a tendency to average out the hard particle protrusions, and a single curve results for all four conditions, peaking between 11 and 11.8 mils with all values well above the specified 10 mils.

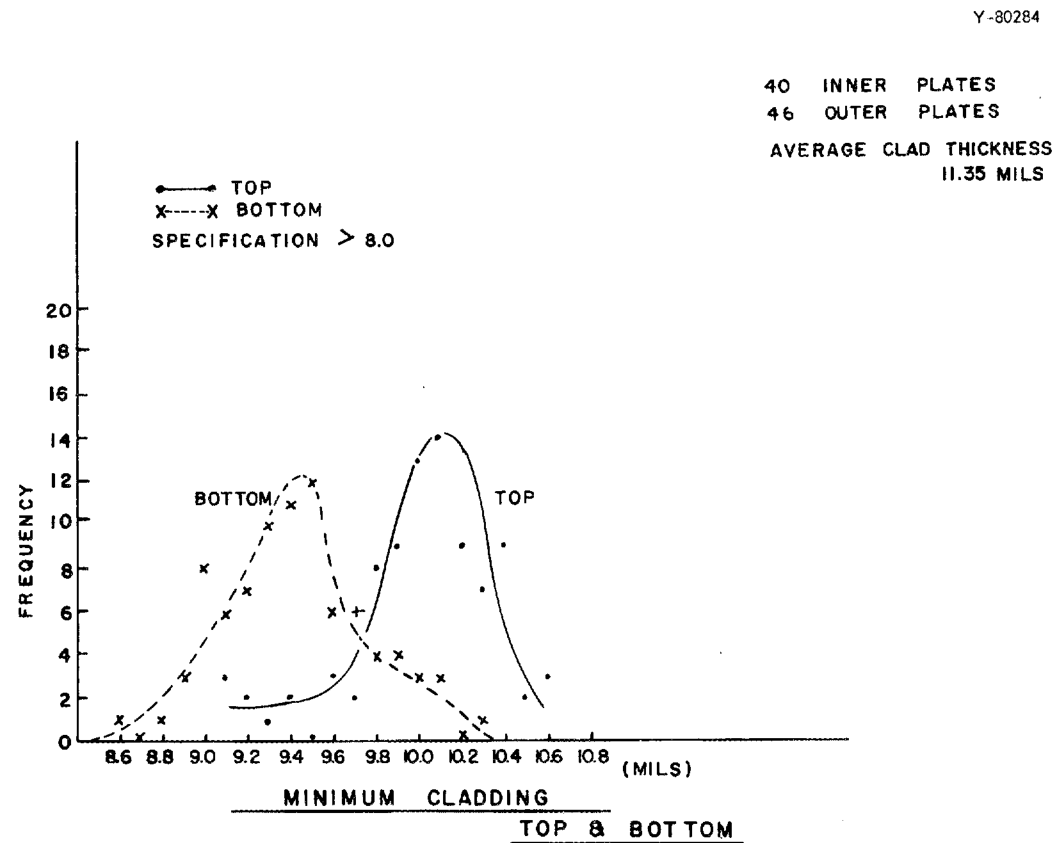

Fig. 10. Minimum Cladding Thickness Variation for HFIR Fuel Plates.

Edge Cladding

We also have quite satisfactory control of both the edge and end cladding. Distribution plots for the width of the edge cladding are presented in Fig. 11. Again, sharp peaks were obtained and the extreme values were well within the specified limits, which are beyond the range of the graph.

Length of end cladding is plotted in Fig. 12. The horizontal lines across the graph show the specified limits. These plotted lengths include end effects resulting from taper, flash, or flaking; any evidence of even a single fuel particle is included. The values for these curves would not include plates rejected by the normal inspection; however,

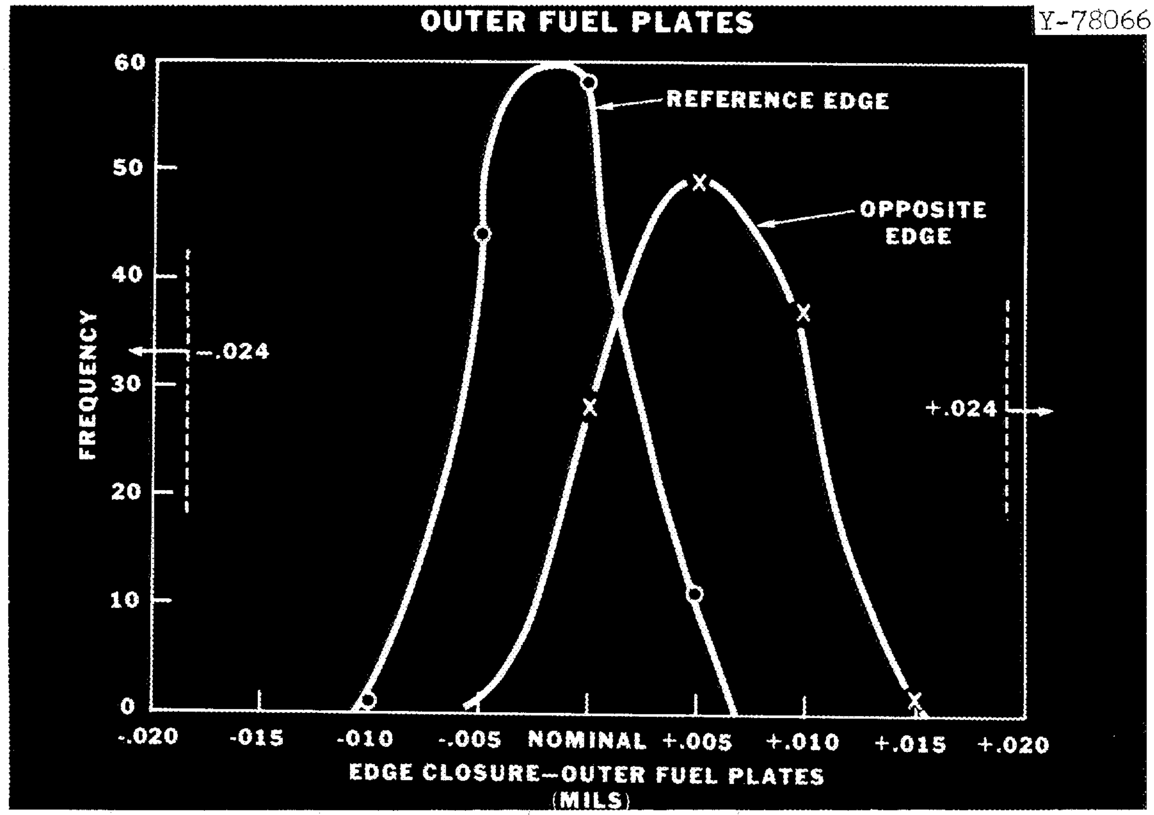

Fig. 11. Edge Closure Variation in HFIR Outer Annulus Fuel Plates.

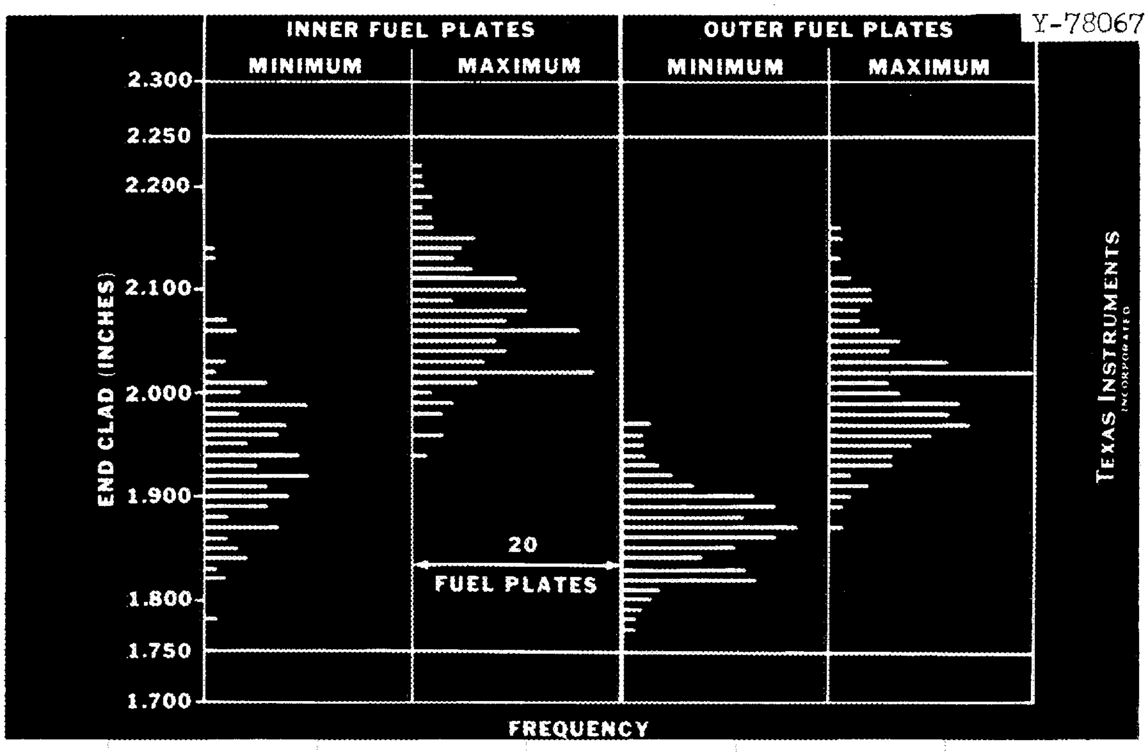

Fig. 12. End Cladding Variations in HFIR Fuel Plates. The minimum and maximum thicknesses are shown for each end of each plate.

such rejections have been consistently less than 1%, as was shown in Fig. 9. These plots show relatively narrow distribution ranges well within the specified limits.

Water-Channel Spacing

Figure 13 demonstrates the control that has been achieved on water-channel spacing for the outer elements. Curves are shown for maximum and minimum values of both the individual spot and cross-section averages. This figure presents the most pessimistic picture possible since it includes the worst value found in 1845 complete longitudinal scans of each element. The element channel spacings were measured immediately after fabrication. In every case, out-of-tolerance values were readily corrected before shipping; most occurred at the plate ends and resulted from expansion problems. Even under these very pessimistic conditions, the data look good; both the element average and the minimum and maximum channel averages are all within tolerance; only a few of the spots are out of tolerance.

Y-85066

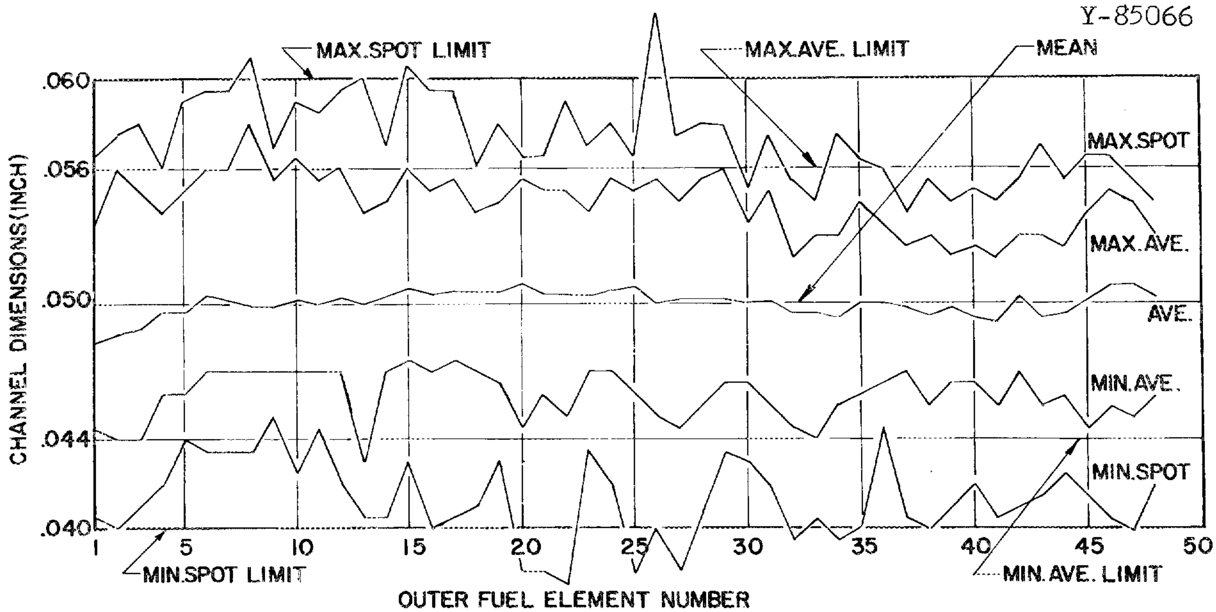

Fig. 13. Outer Annulus Channel Spacing Measurements.

Figure 14 is a plot of similar data from 855 scans for each inner element. The data look even better; only a single maximum average as-fabricated value is out of specification.

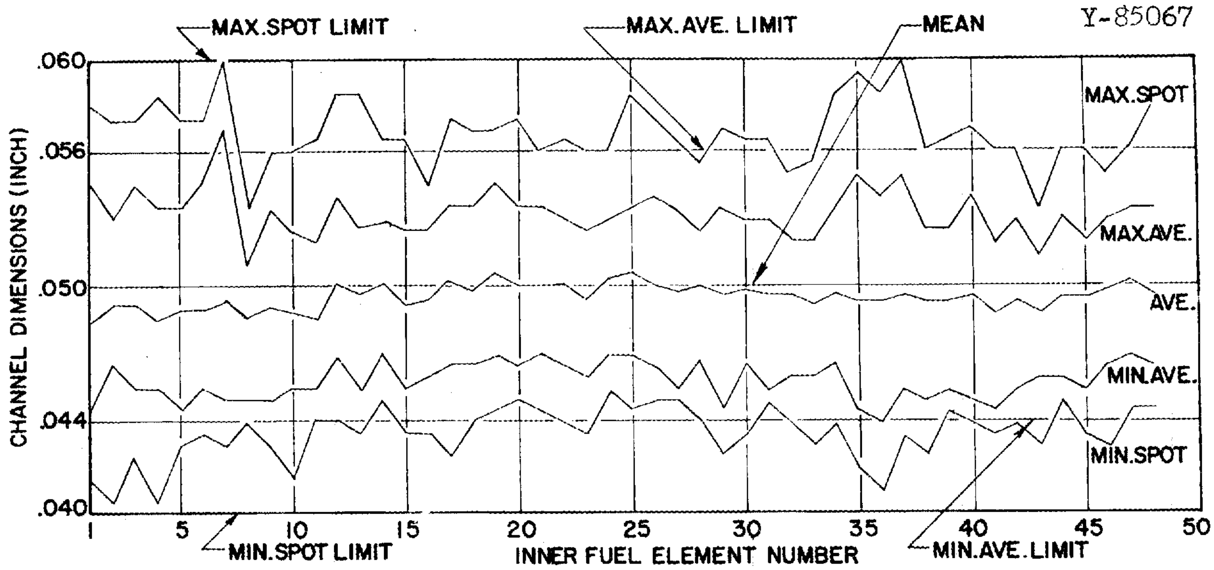

Fig. 14. Inner Annulus Channel Spacing Measurements.

ELEMENT WAIVER SUMMARY

Table 3 illustrates an item with which we are not completely pleased but which is not unexpected. Out of a total of 45 fuel assemblies, only four inner elements and no outer elements have been accepted without a waiver of some kind. After the first five assemblies, the inner elements contained, on the average, two types of defects and 6.5 specification deviations per element; similar figures for the outer element were 3.9 and 12, respectively. However, after careful consideration by the technical staff at ORNL, all elements have been accepted for use at the design power level. We intend to accept all elements; however, we intend to place a maximum limit on the power level at which any that contain serious defects may be operated.

Table 3. Acceptability of 45 HFIR Fuel Assemblies

Elements	Types of Defects	Number of Defects	Number Accepted Without Waivers
Inner			
1–5	4.6	15.5	0
6–45	2	6.5	4
Outer			
1–5	5.6	37.4	0
6–45	3.9	12	0

Table 4 summarizes the total number of defects in elements in groupings of five. For both the inner and outer elements, the waivers arise from a variety of causes. With only a few exceptions, the numbers from the individual causes are small. We can say that all items in the specifications have been met in many elements and only a few single items have appeared in the waiver list with sufficient frequency to require changes in the specifications or procedures. No major or critical changes have been made in the specifications.

CONCLUSIONS

We hope we have shown that HFIR is truly an advanced research reactor pushing the frontiers of the technology. In spite of this, it has been possible to fabricate the unusual fuel elements to very tight specifications. An excellent performance has been obtained with these elements during reactor operation, and a spent element under examination shows remarkably low levels of damage.

Table 4. Number of Defects, HFIR Fuel Elements

Elements	Dimensions	Welds		Plate Spacing	Final Inspection	Plate Waivers	Miscellaneous	Total Number
		Type A	Type B					
Inner								
1–5	3	21	15	11	4	0	24	78
6–10	20	2	1	2	3	0	0	28
11–15	14	0	4	0	5	0	3	26
16–20	0	5	7	0	3	0	1	16
21–25	1	0	5	0	5	9	0	20
26–30	4	8	2	0	0	9	0	23
31–35	2	1	0	0	0	9	2	14
36–40	7	75	1	0	2	17	20	122
41–45	1	0	1	0	1	10	0	13
Outer								
1–5	71	38	12	2	1	0	63	187
6–10	24	0	1	4	9	0	9	47
11–15	5	7	2	8	3	0	9	34
16–20	32	24	7	1	4	20	13	101
21–25	4	4	5	10	4	18	0	45
26–30	10	4	3	5	0	23	0	45
31–35	6	7	5	45	1	49	2	115
36–40	14	1	3	1	1	20	0	40
41–45	10	3	1	2	2	36	0	55

INTERNAL DISTRIBUTION

1–3. Central Research Library
4–5. ORNL Y-12 Technical Library
Document Reference Section
6–149. Laboratory Records
150. Laboratory Records, ORNL, R.C.
151. ORNL Patent Office
152–157. G. M. Adamson
158. R. J. Beaver
159. A. L. Boch
160. G. E. Boyd
161. J. A. Cox
162. J. E. Cunningham
163. J. H. Erwin
164. J. H Frye, Jr.
165. W. O. Harms
166–167. M. R. Hill
168–173. R. W. Knight
174. W. J. Leonard
175. M. M. Martin
176. W. R. Martin
177. R. W. McClung
178. R. McCord
179. C. J. McHargue
180. P. Patriarca
181. G. M. Slaughter
182. D. A. Sundberg

EXTERNAL DISTRIBUTION

183. J. Binns, Metals and Controls Corporation, Attleboro, Mass.
184–185. D. F. Cope, RDT, SSR, AEC, Oak Ridge National Laboratory
186. R. Jones, Research Materials Branch, AEC, Washington
187. V. Kolba, 9700 Cass Avenue, Argonne National Laboratory, Argonne, Illinois
188. C. L. Matthews, RDT, OSR, AEC, Oak Ridge National Laboratory
189. D. Rausch, AEC, Washington
190. J. Simmons, AEC, Washington
191. W. W. Ward, AEC, Washington
192. Division of Research and Development, AEC, Washington
193–207. Division of Technical Information Extension